

Effect of a Dynamic Learning Tutorial on Undergraduate Students' Understanding of Heat and the First Law of Thermodynamics.

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Abstract

We present gains in student conceptual understanding of heat and the First Law of Thermodynamics after use of an active-learning tutorial. We have developed a learning tutorial that addresses common conceptual difficulties about thermodynamics that occurred during an undergraduate physical chemistry course. Our tutorial is interactive, in that it uses a hands-on physical model designed to engage students and allow them to experience various aspects of the concepts being addressed. Students used our tutorial just after completion of a standard semester's coverage of the First Law material. After the tutorial, we measure a normalized gain of 0.70 for students' understanding of internal energy changes associated with changes in heat and/or work. In addition, the percentage of students' possessing a robust understanding of thermal energy exchange (heat) is shown to increase from 69%, after course instruction, to 100% on measures after tutorial use. We also report comparisons between test and control groups on common exam questions pertaining to the First Law of Thermodynamics. Our results show that the two groups performed the same on a standard calculation problem, but the test group who used the tutorial scored substantially higher on the conceptual problem, showing a stronger conceptual understanding of the First Law. This work shows that the learning associated with a single in-class tutorial greatly outweighs any learning that has taken place over a semesters worth of lecture and homework on the given topic.

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Active Learning, Testing/Assessment, Thermodynamics, Physical Chemistry,
Misconceptions

Teaching and learning are not synonymous. Chemistry educators must address how students learn the content within their courses. The use of “student-centered” guided inquiry methods has been shown to aid students in mastering difficult concepts [1-6] and improving their problem solving abilities [4-7]. The purpose of our research is to measure the learning gains associated with a learning tutorial which is designed to address difficult and often-misunderstood concepts within the thermodynamics curriculum of an undergraduate physical chemistry course.

This paper presents results from the use of a hands-on model and learning tutorial in an undergraduate physical chemistry lecture course. These materials are easy to use and suitable for instruction in a lecture setting. The materials address misunderstandings discovered through classroom observation and student interviews about heat and the First Law of Thermodynamics. We first present the difficulties with the concepts as observed in our courses. The tutorial model designed to address these difficulties will be presented and assessed. Our assessment consists of (1) evaluating learning gains with pre- and post-tutorial data and (2) comparing the scores of our test and control groups on identical exam questions.

Student Observations and Interviews

We observed five semesters (a total of 155 students) of undergraduate Physical Chemistry I courses (Thermodynamics and Kinetics) at a large research university to gain insight about the material that students struggle with most. Classroom observations were conducted by one or two observers who attended every class period and recorded notes about the topics covered and the depth of the coverage. Their observations included students' questions about the material being addressed. Informal student interviews were conducted during help room sessions. On average, 2–3 students (~6-10% of the class) attended these sessions at any given time.

The courses began with the First Law of Thermodynamics. Student responses to instructor questions asked during class, and their own questions, revealed that a large fraction of the class struggled with basic First Law concepts presented during the first few class periods. In addition to this coverage in the physical chemistry class, thermal energy exchange (heat) and the First Law of Thermodynamics are both concepts originally introduced (at a basic level) to students during general chemistry. Our findings, as well as the work of others [7-9], show that students do not have a clear conceptual understanding about work, heat, or internal energy. From interviews it also became clear that many students did not believe that there was a difference between “heat” and “temperature.” This confusion has been addressed in many publications [10-12]; it has particularly devastating consequences in a thermodynamics course.

In addition to this belief about the equivalence of heat and temperature, we found that many students cannot correctly identify when thermal energy (heat) is entering or leaving a reaction or process. In discussions about the endothermic reaction that takes place

inside a common ice pack, students' noted that the ice pack (reaction) "feels cold to the touch". When asked what the feeling of "cold" meant, several students stated that "heat must be leaving the reaction because the pack feels cold, it has less energy."

When students were asked to reason through First Law problems involving compressions and expansions, we found that many students began by trying to use the ideal gas equation. For example, students were asked to explain why the temperature of a sample of air trapped inside an insulated cylinder increases as a piston compresses the air. After having already covered the First Law of Thermodynamics material in their course, 43% of the student responses contained explanations based solely on the ideal gas equation and never mentioned work, heat, or internal energy.

Because of these initial difficulties many students struggle to understand other topics in thermodynamics, for example, the Carnot cycle and the state function derivation covered under the Second Law.

Study Design

We investigated students' conceptual understanding of heat and the First Law of Thermodynamics in an undergraduate physical chemistry course ($N = 32$). The course was the first semester of a year long sequence for chemistry and biochemistry majors. The course was taught by a senior faculty member who regularly taught the physical chemistry sequence. The instruction format was traditional lecture style for 50 minutes, three times a week. Weekly homework consisted of standard quantitative analysis and derivations. Before any conceptual assessment or tutorial use took place, students received 2 weeks of instruction and 2 homework sets on the First Law material.

Before tutorial use, a pre-tutorial quiz was given. The quiz consisted of three short answer questions about work, heat, and internal energy. Students worked independently on the quiz and were given ten minutes to complete it. During the remainder of the period (40 minutes), students performed the tutorial in groups of 3-4. A post-tutorial quiz (identical questions to the pre-quiz) was given during the first ten minutes of the following class period. Both quizzes were scored using the rubrics in Tables 1 and 2.

In addition to the pre-post testing, conceptual understanding was measured during the first course exam, two weeks after the tutorial use. The short answer question, about temperature change and internal energy during an adiabatic compression, was scored using Table 2. Our test group's scores on this exam question were compared to a control population.

The control group consisted of 22 students enrolled in a similar physical chemistry course. The test and control courses were taught by different instructors. Both used traditional lecture formatting, quantitative homework assignments, and the same text book. Lecture time and the number of quantitative homework sets on the First Law were identical between the groups. To offset some of the time-on-task differences between the sections, the control group was given three additional short answer homework problems on the First Law. After these conceptual problems were graded and returned, the answers were discussed in class providing an additional 20 minutes of lecture time.

The uniformity of the two groups was measured in two ways. First, at the start of the semester we checked for differences in students' incoming knowledge using a physical chemistry conceptual exam. The concept exam was developed by another researcher at the University of Colorado and is not published. The exam contained 34 questions (true/false

and multiple choice) covering thermodynamics and kinetics. The average scores of the test and control groups were compared in order to correlate differences due to the populations. Second, an additional identical exam question was compared between the two groups. The second question was a standard quantitative problem on the First Law, for which we expect to see no difference between the groups based solely on tutorial use.

Tutorial Outline and Observations

During the development stages of our tutorial, we recorded field notes about student interactions with and comments about the tutorial. Here we present our observations of these 57 students (working in groups of 3-4) along with the tutorial format. In our tutorial a can of compressed gas is used as a model for adiabatic expansion. With this model, students can feel the effect of the expanding gas on the temperature. In fact, many students have reported that they noticed temperature decreases when using compressed gases at home but have never thought about it in terms of thermodynamics.

To start, students were shown a closed system consisting of a can of compressed gas with a balloon over the top. They were asked to make a prediction about how the temperature of the gas in the can changes when the gas is allowed to quickly expand into the balloon. Students were asked to discuss their individual predictions and explanations with their group and to try and come to a consensus. Once the groups have decided on their explanations, each was allowed to test their prediction using the air cans and feeling the temperature change. During the prediction portion, greater than 90% of the students discussed the possibility of using the ideal gas equation to explain any temperature change upon expansion. Most students correctly predicted that the can would cool; however, less than 10% provided correct thermodynamic reasoning for this observation.

The remainder of the tutorial is structured around the individual concepts of heat and work and how they affect the internal energy during both an adiabatic and an isothermal expansion. First, the students were shown Figure 1 and asked to discuss any work that occurred after removal of the masses and if the direction of the work was the same for both systems. Observations showed that the students' possessed a strong grasp of the work concept, as very little discussion (< 1 minute) was needed to obtain group consensus. Next, students were asked to discuss any differences between the thermal energy exchanges that occur during the expansions. During this portion, discussions lasted around 5-6 minutes. Most students needed to first confirm what it meant to be adiabatic or isothermal. This line of reasoning led groups to decide which system underwent an exchange of thermal energy. However, it was observed that no group associated either system with a temperature change at this point. It was not until students were asked to discuss and explain how the work and thermal energy exchange for each individual system affects the internal energy that students began to question temperature changes. It was here that we observed students' misconceptions about the connection between thermal energy exchange (heat) and temperature. Many students (35%) equated heat and temperature, stating that if a given process is adiabatic then "there is no temperature change because $q=0$ ". After group discussion (some lasting as long as 10 minutes) all students came to the correct conclusions regarding the internal energy change for the two systems.

After completing the tutorial worksheet, students were then asked to re-visit the air can problem and discuss the thermodynamic reasoning for the gas getting cold upon expansion. At this point, all groups provided correct thermodynamic reasoning for the temperature decrease upon expansion.

Pre-Post Testing Results

The tutorial session took place during a standard lecture meeting of a first semester physical chemistry course ($N = 32$). In the first question on the pre-tutorial quiz, students were shown a picture of an ideal gas trapped in a non-insulated cylinder by a piston. The question stated that a heavy block was dropped on the piston, compressing the gas. Students were asked if work was done ON or BY the trapped gas and to explain their reasoning. In the second question, students were asked if there was an exchange of thermal energy during this compression, and if there was a transfer, in what direction was the flow. In the final question, students were given a picture of an insulated cylinder where an ideal gas was trapped by a piston. The question stated that the piston was pushed in; students were asked to explain how this compression impacted the internal energy and temperature of the trapped gas. The student responses were scored using the rubrics presented in Tables 1 and 2. Student pre and post tutorial scores are presented in Table 3.

It is clear from the results presented in Table 3 that the students have a good pre-tutorial grasp of whether work is being done ON or BY a gas. This is reflected in question one where all the students respond correctly and provided correct reasoning both before and after the tutorial. However, this is not the case when we consider the responses about thermal energy exchange in question two. After course instruction and before tutorial use, we see that 19% of the responses reflect little to no understanding (rubric score = 0) about thermal energy exchange for the process of compressing a gas. An additional 12% state that there is a transfer of thermal energy but do not know in which direction or why. We see that after the tutorial, only 3% of the responses reflect a totally incorrect response. A normalized learning gain of 0.62 is calculated for all students. In question three, students must tie

concepts together in order to fully address the change in internal energy and temperature of a compressed gas. Nearly 70% score a pre-tutorial 2 or less on the rubric, indicating some lack of important conceptual information. This number drops to 19% after tutorial use. In addition to the large decrease in scores reflecting little to no conceptual understanding, we also calculate a normalized gain of 0.70 for question three. These post-tutorial gains are large and become more significant when we recall that these students have already covered a full semester's worth of material on the First Law.

Control Group Comparison Results

Before comparing our test and control groups with respect to the First Law, we present results of a pre-semester concept exam. This exam will allow us to normalize any differences based on population. On the concept exam, the control group's average score was 49.2% with the test group scoring slightly higher at 56.3%. This 7.1% difference has a calculated p-value of 0.15, and therefore the scores are interpreted as not statistically different. This measure allows us to compare the groups' knowledge of the First Law based on learning during their respective physical chemistry courses and not on previous exposure.

We now compare the results of our test and control groups on identical exam questions. The scores for the exam questions, given on the first exam in each course, are presented in Figure 2. Here we see comparisons for a short-answer conceptual question, a standard calculation question, and an additional category labeled "rubric graded." This final category reflects scoring of the conceptual question by Jack Barbera using the rubric presented in Table 2. The other two categories are the scores assigned by the individual course instructors. In reviewing the scores in Figure 2, we see that both groups have nearly identical average scores on the calculation problem. However, when comparing scores on

the conceptual problem, the test group's average score is much higher than the control group. These results indicate that the two groups possess similar abilities when solving numerical problems but the test group has a more robust conceptual understanding of the material.

The scoring of the conceptual question using the rubric reflects the same trend as the instructor grading. The similarity in these two measures ensures that neither instructor over/under-scored their own exam and that the expectations of student performance are similar between the researchers and instructors.

We also note that the test group's score on the conceptual question remained high (85-90%) two weeks after the tutorial use. While this is not considered "long-term" retention, it does show that the tutorial learning gains were not just an artifact of immediate post-tutorial testing.

Conclusions

We have developed a learning tutorial, which incorporates a hands-on physical model, to aid students' conceptual development of often difficult to grasp material on the First Law of Thermodynamics. This tutorial can be easily implemented during a lecture period and provides a "real-world" experience of a common thermodynamic concept.

We have shown that after a typical semester's coverage of material on the First Law of Thermodynamics, use of this tutorial can produce significant learning gains. These gains are based both on students' knowledge before tutorial use and in comparison with a control group. A normalized gain of 0.70 is measured for students' conceptual understanding of the First Law and significant improvement is observed in students' understanding of thermal energy exchange (gain = 0.62). When compared to a control group, tutorial performers score

equally well on numerical problems but possess a more robust understanding of the underlying concepts.

Further investigations are underway to determine differences in long-term retention due to tutorial use. The practice of using real-world models that students can interact with is thought to promote greater conceptual retention. As this tutorial addresses some of the fundamental concepts of thermodynamics, it would be valuable to measure its impact on learning gains in more difficult areas which build on this material. A logical placement of this type of tutorial would be in the general chemistry curriculum where this material is first encountered. This may provide students with a more robust initial conceptual understanding leading to even greater learning gains in future topics.

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Table 1. Grading rubric used for quiz questions 1 and 2

| Rubric Score | Criterion |
|--------------|--|
| 0 | Student has no idea or student response is totally incorrect. |
| 1 | Student responds correctly to question but provides incorrect reasoning. |
| 2 | Student responds correctly to question and provides correct reasoning. |

Table 2. Grading rubric used for quiz question 3 and exam question

| Rubric Score | Criterion |
|--------------|--|
| 0 | Student has no idea or student response is totally incorrect or irrelevant as compared to the expert response on the central concept(s). |
| 1 | Student response includes some aspects of the expert response on the central concept(s) but major aspects of the expert response on the central concept(s) are missing or incorrect. |
| 2 | Student response essentially matches expert response on the central concept(s) but one important aspect of the central concept(s) is missing or incorrect. |
| 3 | Student response matches expert response on the central concept(s) but minor details concerning the central concept(s) are missing or incorrect. |
| 4 | Student response matches the expert response on the central concept(s). |

Table 3. First Law of Thermodynamics pre and post quiz results and pre-post gains. Data reflects percentage of students with each individual rubric score. Questions 1 and 2 are scored using Table 1, question 3 is scored using Table 2.

| Question | | Rubric Score | | | | | |
|------------------------------------|------|--------------|----|-----|----|----|-------|
| | | 0 | 1 | 2 | 3 | 4 | gain* |
| 1 (work) | Pre | 0 | 0 | 100 | | | |
| | Post | 0 | 0 | 100 | | | |
| 2 (heat) | Pre | 19 | 12 | 69 | | | 0.62 |
| | Post | 3 | 12 | 85 | | | |
| 3 (ΔT and ΔU) | Pre | 35 | 23 | 11 | 23 | 8 | 0.70 |
| | Post | 0 | 4 | 15 | 35 | 46 | |

*This is a normalized gain score calculated as $[(\text{AVG post} - \text{AVG pre}) / (\text{max score} - \text{AVG pre})]$. The average values were derived from the individual student gains, calculated as post score minus pre score.

Figure 1: Barbera and Wieman

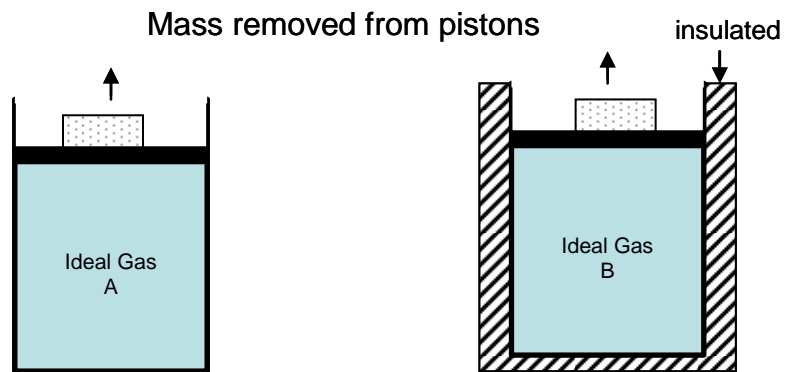


Figure 2: Barbera and Wieman

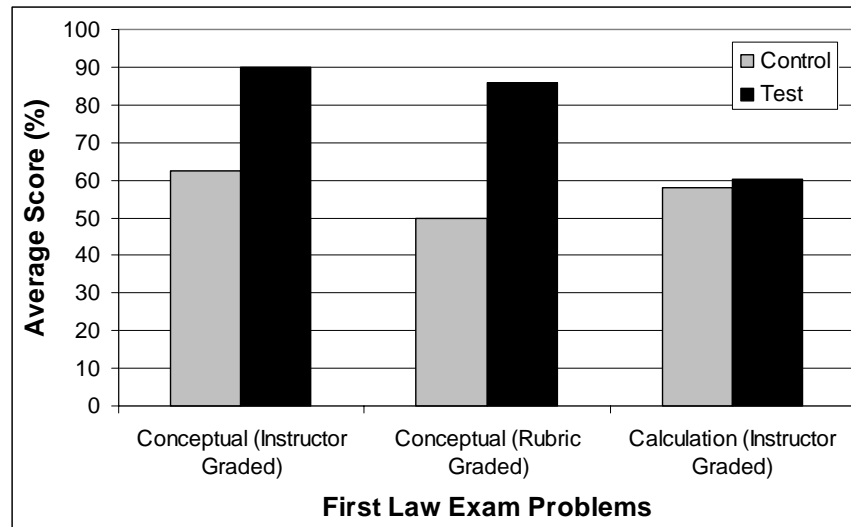


Figure 1. Tutorial example showing a closed (A) and an isolated (B) system with mass being removed to allow expansion of the gas.

Figure 2. Comparison of average scores for control and test groups on common questions. Rubric score reflects average score on conceptual question using rubric presented in Table 2. The difference between the two groups on the conceptual scorings are statistically significant at the $p < 0.01$ level.